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The Zeeman Effect : a Tool for Atom Manipulation

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Abstract

We review in this paper experiments which have been carried out during the last fifty years and which use the Zeeman effect, in conjunction with other effects, for manipulating the various degrees of freedom of an atom. We consider first the internal degrees of freedom and we show how the polarization selection rules of the Zeeman effect have played an essential role in the development of optical methods, such as double resonance or optical pumping, allowing one to control and to detect the polarization of atomic states. The importance of linear superpositions of Zeeman sublevels (Zeeman coherences) is emphasized as well as the possibility to change the Zeeman splittings by non resonant optical or RF fields. The second part of the paper will review more recent experiments where spatially dependent Zeeman shifts are used to control the position and the velocity of a neutral atom. Various schemes will be described, such as Zeeman slowers, Sisyphus cooling, magneto-optical traps, magnetostatic traps, which have been developed recently and which have just culminated with the observation of Bose-Einstein condensation.

1 Introduction

The initial purpose of this paper was to review the applications of the Zeeman effect in modern atomic physics. In fact, the scope of such a paper would have been too broad. There are practically no experiments in atomic physics where Zeeman sublevels, Zeeman shifts or magnetic couplings are not involved! I have thus thought that it would be more appropriate here to try to find a simple guideline along which I could organize this paper and which would allow me to put in perspective several important developments which have occurred during the last fifty years. In this respect, atom manipulation is a good guideline because the Zeeman effect turns out to play an essential role in the different methods which have been developed for controlling the various degrees of freedom of an atom.

Consider first the internal degrees of freedom of an atom, i.e. its angular momentum and its energy. By playing with the polarization selection rules of the Zeeman effect, which result from the conservation of the total angular momentum of the atom–photon system in absorption or emission processes, it is possible to prepare an atom or to detect its presence in a given Zeeman sublevel $|M\rangle$, or in a linear superposition of such sublevels $\sum_M c_M|M\rangle$. The first part of this paper will be devoted to a review of several developments based on these ideas, such as double resonance, optical pumping, Hanle effect, quantum beats, etc. Another interesting topic is the possibility to use non-resonant optical or RF fields for perturbing the energy of Zeeman sublevels. Non-resonant light produces light shifts which can vary from one Zeeman sublevel to another, and which thus change the Zeeman splittings. A high frequency non-resonant RF field can modify, and even cancel the g-factor of an atomic state, giving rise to dressed magnetic moments. All these developments, which have taken place from the early fifties to the middle seventies, do not rely on the monochromaticity of the exciting light, but only on its polarization. This explains why they predate the use of lasers in atomic physics.

The second part of the paper will deal with the external degrees of freedom of atoms, i.e. their position and their velocity. Then, the monochromaticity of laser sources can be combined with spatially varying Zeeman shifts for controlling the exchanges of linear momentum between atoms and photons. A lot of new developments have occurred since the early eighties, concerning the possibility to slow down, to cool and to trap atoms. A few of them

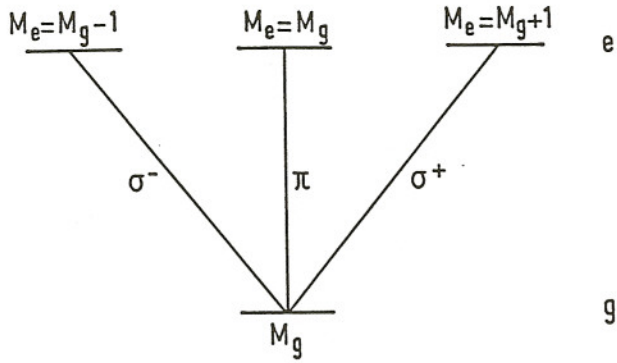

Figure 1: Polarization of the various Zeeman components of an optical line

will be briefly reviewed, such as Zeeman slowers, Sisyphus cooling, optical lattices, magneto-optical traps, magnetostatic traps. These developments have culminated recently with the observation of Bose-Einstein condensation on alkali atoms. Several contributions in this volume are devoted to these problems. It is clear that a new research field is being opened by these new states of matter, and that the Zeeman effect will continue to find applications in this domain.

2 Internal degrees of freedom

2.1 Preparing or detecting an atom in a given Zeeman sublevel

Recall first the well known polarization selection rules for the various Zeeman components $|g, M_g\rangle \longleftrightarrow |e, M_e\rangle$ of an optical line connecting a ground state g to an excited state e, M_g and M_e being the magnetic quantum numbers labelling the eingenvalues of the total atomic angular momentum along the quantization axis. For electric dipole transitions, $\Delta M = M_e - M_g = -1, 0, \text{or} + 1$. Fig. 1 gives the polarization corresponding to each value of ΔM: σ^+ for $\Delta M = +1$, π for $\Delta M = 0$, σ^- for $\Delta M = -1$. These results are a direct consequence of the conservation of the total angular momentum [1]. Photons corresponding to σ^+–polarized light (resp. σ^-) have an angular momentum along the axis of quantization equal to $+\hbar$ (resp. $-\hbar$),whereas

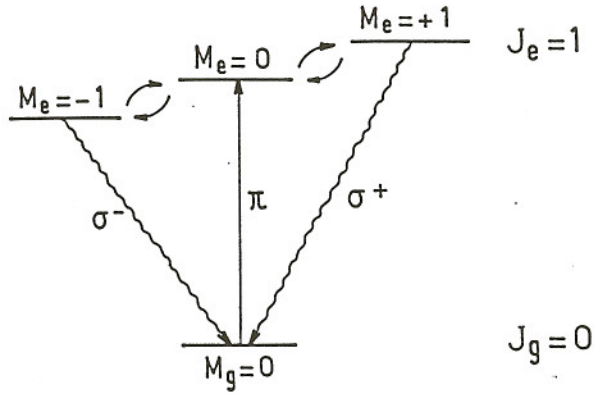

Figure 2: Principle of the double resonance method for a transition $J_g = 0 \longleftrightarrow J_e = 1$. Atoms are selectively prepared in the sublevel $M_e = 0$ by excitation with π-polarized light. During the time spent in the excited state, resonant radiofrequency transitions transfer them from $M_e = 0$ to $M_e = +1$ and $M_e = -1$. Such transfers are detected by monitoring the σ^+ or σ^- fluorescence light reemitted by the atom.

π-polarized photons have an angular momentum equal to 0. This is precisely the angular momentum which is gained by the atom when it absorbs such a photon and is excited from M_g to M_e.

Consider an atom with a transition $J_g = 0 \longleftrightarrow J_e = 1$. By exciting it with resonant light having a well defined polarization, σ^+ , σ^- or π, it is thus possible to prepare it in a well defined excited Zeeman sublevel. Similarly, by monitoring the fluorescence light reemitted by such an atom with a well defined polarization, one can infer from what Zeeman sublevel the photon has been emitted. This is the principle of the double resonance method [2, 3], which is recalled in Fig. 2 and which is an optical method for studying magnetic resonance in atomic excited states.

Optical methods also apply to atomic ground states having several Zeeman sublevels. Angular momentum can be transferred from polarized photons to atoms in absorption–spontaneous emission cycles. The principle of such a method, called optical pumping [4], is recalled in Fig. 3 for a transition $J_g = 1/2 \longleftrightarrow J_e = 1/2$. It allows one to achieve high degrees of spin polarization in the ground state. Since the amount of absorbed light depends

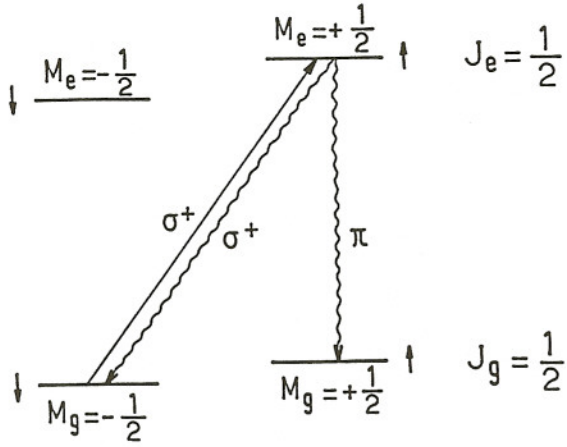

Figure 3: Principle of the optical pumping method for a transition $J_g = 1/2 \longleftrightarrow J_e = 1/2$. Atoms are selectively excited from $M_g = -1/2$ to $M_e = +1/2$ by excitation with σ^+-polarized light. From there, they fall back in the ground state by spontaneous emission of a photon which can be, either σ^+-polarized, in which case the same cycle can be repeated, or π-polarized, in which case the atom remains trapped in $M_g = +1/2$. After such an optical pumping cycle, the ground state becomes fully polarized in the $M_g = +1/2$ sublevel. Note that the absorption of the incoming σ^+ light is directly proportional to the population of the $M_g = -1/2$ sublevel, which provides an optical detection signal for monitoring the variations of this population.

on the relative populations of the ground state Zeeman sublevels, it is also possible to detect optically any variation of these populations due to resonant radiofrequency transitions or to relaxation processes.

2.2 Linear superpositions of Zeeman sublevels–Zeeman coherences

When the polarization of the exciting light (or of the detected fluorescence light) is a linear superposition of the basic polarizations σ^+, σ^- and π, the atom is prepared (or detected) in a linear superposition of excited Zeeman sublevels. The atomic density matrix σ has then off–diagonal elements $\sigma_{12} = \langle 1|\sigma|2\rangle$ (where 1 and 2 are shorter notations for M_e and M'_e), which are called

"Zeeman coherences"[5]. They are at the origin of several interesting effects which can be observed using the fluorescence light which is emitted by the atom and which depends not only on the populations σ_{11} and σ_{22} of the two sublevels $|1\rangle$ and $|2\rangle$, but also on the Zeeman coherences σ_{12} and σ_{21}. These effects result from quantum interferences between two emission amplitudes starting from the two sublevels $|1\rangle$ and $|2\rangle$ and ending into the same ground state sublevel. We review now a few of them.

It is convenient for that to start from the equation of motion of σ_{12}, which may be shown to have, in several important cases [5, 6], the following form

$$\dot{\sigma}_{12} = R - i\frac{E_1 - E_2}{\hbar}\sigma_{12} - \Gamma\sigma_{12} \tag{1}$$

The various factors which determine the rate of variation of σ_{12} are: the optical excitation, which prepares σ_{12} at a rate R; the free evolution in the magnetic field $\mathbf{B}$ at the Larmor frequency $(E_1 - E_2)/\hbar$; the damping with a rate Γ due to spontaneous emission. We can now look for the solution of equation (1) in a certain number of cases.

Suppose first that the intensity of the exciting light beam is constant. R is then constant, and equation (1) has a steady-state solution.

$$\sigma_{12} = \frac{\hbar R}{i\,(E_1 - E_2) + \hbar\Gamma} \tag{2}$$

which clearly exhibits resonant variations when the magnetic field $\mathbf{B}$ is scanned around zero, in an interval determined by $\mid E_1 - E_2 \mid \leq \hbar\Gamma$. This provides a quantitative interpretation of the zero field level crossing resonance, which is called also the Hanle effect [7]. The same equation (1) also explains why level crossing resonances can be observed near values of the magnetic field where two Zeeman sublevels $|1\rangle$ and $|2\rangle$ belonging to two different hyperfine levels cross. This is the Franken effect[8] and $\langle 1|\sigma|2\rangle$ is then a hyperfine coherence.

Suppose now that one uses a modulated excitation :

$$R = R_0 e^{-i\Omega t} \tag{3}$$

Equation (1) then admits a solution of the form :

$$\sigma_{12}(t) = \frac{\hbar R_0}{i\,(E_1 - E_2 - \hbar\Omega) + \hbar\Gamma} e^{-i\Omega t} \tag{4}$$

which shows that σ_{12} is modulated at the same frequency Ω as the exciting light and exhibits resonant variations when $E_1 - E_2$ is scanned around $\hbar\Omega$. Such resonant modulations of the fluorescence light have been first observed on cadmium atoms [9].

Another interesting situation is found when one uses a percussional excitation :

$$R = R_0\delta(t) \tag{5}$$

$\delta(t)$ being the delta fonction (more physically, one uses a pulse of exciting light, with a duration much smaller than $\hbar/|E_1 - E_2|$ and $1/\Gamma$). For $t > 0$, the solution of equation (1) reads

$$\sigma_{12}(t) = R_0 e^{-i(E_1-E_2)t/\hbar} e^{-\Gamma t} \tag{6}$$

Such damped oscillations at the frequency $(E_1 - E_2)/\hbar$ are nothing but the so-called "quantum beats" and they have been first observed in 1964 on cadmium atoms [10].

Note also that, even if it is not prepared directly by the optical excitation ($R = 0$), σ_{12} can build up from $\sigma_{11} - \sigma_{22}$ under the effect of a resonant radiofrequency field $\mathbf{B}_1 e^{-i\Omega t}$, perpendicular to $\mathbf{B}$. Modulations then appear in σ_{12} which are resonant when the frequency Ω of the RF field is close to $(E_1 - E_2)/\hbar$. The corresponding modulations at frequency Ω of the fluorescence light have been called "light beats" [11]. In fact, one of the first demonstrations of the importance of Zeeman coherences was the observation of a narrowing of the double resonance curves in the excited state of mercury atoms when the density of the atomic vapour increases [12]. The Zeeman coherence induced in the excited state by the RF field is partially transferred from this atom to another one by multiple scattering of resonance radiation and this explains why the effective lifetime of Zeeman coherences becomes longer at higher vapour pressures leading to more efficient imprisonment of resonance radiation.

All the previous considerations can be easily extended to atomic ground states. Zeeman coherences are associated with the existence of an anisotropy of the atomic orientation or alignment in the plane perpendicular to $\mathbf{B}$. Such a transverse orientation or alignment can be prepared in the ground state by a transverse optical pumping, perpendicular to $\mathbf{B}$, or by applying a resonant RF (or microwave) field to a longitudinally oriented or aligned vapour.

Equations similar to (1) can be established [5], allowing one to interpret resonances similar to those described above. Because relaxation times are much longer in the ground state g than in the excited state e, these resonances are much narrower. For example, zero field level crossing resonances have been observed in the ground state of rubidium atoms, which are so narrow that they can be used to detect very weak magnetic fields, on the order of 3.10^{-10} Gauss [13, 14].

2.3 A few important features of optical methods

The various schemes described in the previous subsections are called "optical methods" because they use light for both the preparation and the detection of the atomic state. We summarize here a few important features of these methods.

First, they provide very large polarizations at room temperature and in low magnetic fields. This is due to the fact that they do not rely on the Boltzmann factor $\exp(-H_{\text{Zeeman}}/k_B T)$. For the same reason, they can be applied to states having a purely nuclear paramagnetism ($J = 0$ and $I \neq 0$). Optical pumping methods are thus very efficient for polarizing nuclear spins, which can lead to interesting applications, such as the magnetic resonance imaging of human organs (see for example the contribution of E. Otten in this volume and the references therein).

Optical methods have also a very high sensitivity. The magnetic resonance is detected, not by measuring the absorption of the RF or microwave power, but by monitoring a modification of the light absorbed or emitted by the atoms. One can thus study very dilute media, such as atomic vapours.

Finally, optical methods are not sensitive to the optical Doppler effect. Zeeman splittings, fine or hyperfine structures are not determined from a difference between two optical frequencies. They are measured directly from the frequency of the resonant RF or microwave field, or from the evolution frequency of a Zeeman or hyperfine coherence. This explains why it has been possible to develop a high resolution spectroscopy before the advent of monochromatic laser sources.

2.4 Perturbing Zeeman splittings with nonresonant optical or RF fields

If the exciting light is detuned from resonance, one can show [5, 6] that it produces energy shifts of the ground state Zeeman sublevels, called "light shifts" or "ac Stark shifts". The magnitude of such light shifts is proportional to the light intensity and inversely proportional to the detuning $\delta = \omega_L - \omega_A$ between the laser frequency ω_L and the atomic frequency ω_A (in the limit when the Rabi frequency Ω_1 describing the light-atom interaction is small compared to $|\delta|$). Because of the polarization selection rules, light shifts depend on the polarization of the exciting light and vary from one Zeeman sublevel to another.

For example, in the case of the transition $J_g = 1/2 \longleftrightarrow J_e = 1/2$ of Fig. 3, a σ^+-polarized exciting light shifts only the sublevel $M_g = -1/2$ (if $\omega_L \neq \omega_A$), whereas a σ^-–polarized light shifts only the sublevel $M_g = +1/2$. The Zeeman splitting between the two sublevels can thus be changed by a nonresonant light (see Fig. 4), which produces a shift of the magnetic resonance curve in the ground state. The sign of this shift changes when the polarization of the exciting light changes from σ^+ to σ^-. Because magnetic resonance curves are very narrow in the ground state, it is possible in this way to detect very small light shifts, on the order of one Hertz, produced by the light emitted by a discharge lamp [15]. Now, with laser sources, light shifts on the order of one Gigahertz can be easily produced.

In the absence of external magnetic fields, light shifts can remove the Zeeman degeneracy and their effect is equivalent with the one which would be produced by dc "fictitious " magnetic or electric fields [16, 17].

Light shifts can be considered from different points of view. First, they are "stimulated" radiative corrections, which can be interpreted as resulting from virtual absorptions and reemissions of photons by the atom. In this respect, they are the equivalent, for the absorption-stimulated emission process, of the Lamb shift for spontaneous emission. Secondly, they introduce perturbations to high precision measurements using optical methods, which must be taken into account before extracting from these measurements spectroscopic data. Finally, they are now more and more frequently used for manipulating the energy of Zeeman sublevels. For example, it is easy to produce a light field whose polarization changes from σ^+ to σ^- every quarter of wavelength (see Fig. 6). From Fig. 4, we then deduce that one can produce in this way spatial

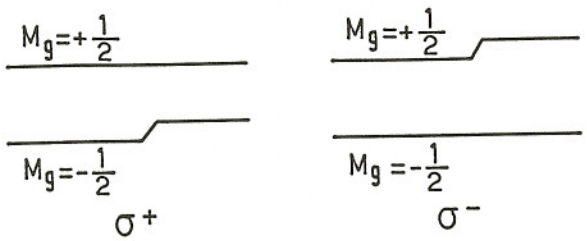

Figure 4: Light shifts of the ground state Zeeman sublevels for the transition $J_g = 1/2 \longleftrightarrow J_e = 1/2$ of Fig. 3. The Zeeman degeneracy is removed by a static magnetic field. The light beam exciting the transition is slightly detuned from resonance. The detuning δ is positive, so that light shifts are positive. Depending whether the light polarization is σ^+ or σ^-, only Zeeman sublevel $M_g = -1/2$ or $M_g = +1/2$ is light-shifted.

modulations of the Zeeman splittings on an optical wavelength scale, which would not be easily achieved with real magnetic fields. We will see in the next section interesting applications of such a situation.

Zeeman splittings can be also modified by nonresonant RF fields. In particular, it can be shown that the g–factor of an atomic state can be reduced, and even cancelled by a high frequency nonresonant RF irradiation [18, 19]. Such an effect has been calculated in a nonperturbative way with the dressed atom approach. One can also interpret semiclassically why the effective magnetic moment of the atom is reduced by the interaction with the RF field. The motion of the magnetic moment in the RF field consists of an angular vibration of the direction of this magnetic moment which keeps a constant length. Averaging over one period of the RF field can only lead to a decrease of the static component of the magnetic moment.

It is then tempting to consider that such a "stimulated" radiative correction is analogous to the electron spin anomaly $g - 2$. However, applying the same picture to the motion of the electron spin in vacuum fluctuations would predict a decrease of g from the value 2 (in the absence of radiative corrections), whereas it is well known that $g - 2$ is positive. The answer to this paradox is that g is defined from both the Larmor frequency Ω_L of the

spin and the cyclotron frequency Ω_C of the charge by the relation

$$g/2 = \Omega_L/\Omega_C \tag{7}$$

It is not enough to consider the radiative corrections to the Larmor frequency of the spin. One must also consider the modifications of the cyclotron motion. One then finds [20] that both Ω_L and Ω_C are reduced, Ω_C being more reduced than Ω_L, so that g becomes larger than 2 according to equation (7). The physical interpretation of such a result, in the nonrelativistic domain, is that a charge is more coupled to its self field than a magnetic moment, which results in a more efficient slowing down of the cyclotron motion. A full relativistic calculation, to all orders in $1/c$, but to order 1 in the fine structure constant α, confirms this interpretation [21]. Similar conclusions have been obtained from a different approach [22]. Finally, such a discussion shows that, for understanding $g-2$, it is necessary to consider the modification of the motion of both the charge and the spin of the electron. There is here a certain analogy with the situation encountered when one tries to interpret the "anomalous" Zeeman effect. Such an effect cannot be understood by considering only the motion of the charge in the applied magnetic field. One must also take into account the magnetic coupling of the spin.

3 External degrees of freedom

3.1 Zeeman slowers

We review now a few mechanisms using spatially dependent Zeeman shifts for controlling the position and the velocity of a neutral atom, and we begin by describing the so-called "Zeeman slowers" which are used for decelerating and stopping an atomic beam [23, 24].

Consider an atomic beam which is irradiated by a counterpropagating resonant laser beam (see Fig. 5). Photons are absorbed from the laser beam and spontaneously reemitted in all possible directions. In an elementary absorption-spontaneous emission cycle (fluorescence cycle), the average momentum transferred to the atom is equal to the momentum $\hbar\mathbf{k}$ of a laser photon, because spontaneously emitted photons have equal probabilities to be emitted in opposite directions and their mean momentum is equal to zero. When the atomic transition is saturated, the mean number of fluorescence

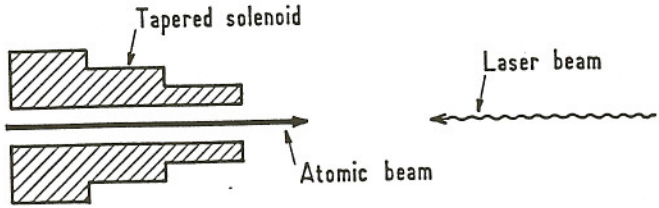

Figure 5: Principle of a Zeeman slower. The radiation pressure force exerted on an atomic beam by a counterpropagating resonant laser beam decelerates the atoms. The Doppler shift due to such a deceleration is compensated for by a spatially dependent Zeeman shift associated with an inhomogeneous magnetic field produced by a tapered solenoid. This allows the laser beam to remain in resonance with the atoms during the whole deceleration process.

cycles per unit time is equal to $\Gamma/2$, where Γ is the spontaneous emission rate (the atom spends half of its time in the upper state). It follows that the mean radiation pressure force experienced by the atom is equal to $\hbar k\Gamma/2$, leading to a mean acceleration (or deceleration) given by

$$a_{\mathrm{Max}} = \frac{\hbar k}{M}\frac{\Gamma}{2} = v_R\frac{\Gamma}{2} \tag{8}$$

where $v_R = \hbar k/M$ is the recoil velocity of an atom absorbing a laser photon. Such a recoil veloity is usually very small, on the order of $10^{-2}\,\mathrm{m.s^{-1}}$. But Γ can be very large, on the order of $10^8\,\mathrm{s^{-1}}$, so that a_{Max} can reach values on the order of $10^6\,\mathrm{m.s^{-2}}$, *i.e.* 10^5 times the acceleration of gravity.

There is however a difficulty due to the Doppler shift associated with the deceleration. Such an effect shifts the atoms out of resonance and the mean radiation pressure force decreases. This is precisely where Zeeman shifts can be useful. The Doppler shift due to the deceleration process can be compensated for by a spatially dependent Zeeman shift associated with the inhomogeneous magnetic field produced by a tapered solenoid (see Fig. 5). Such a scheme, now called Zeeman slower, has been first demonstrated with sodium atoms [23, 24]. It is quite general and it allows the deceleration to

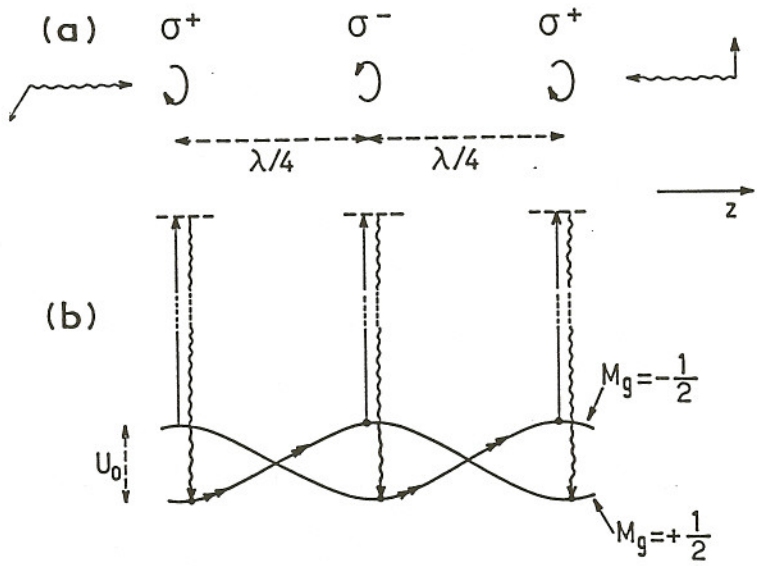

Figure 6: a–Laser configuration formed by two counterpropagating plane waves along the z-axis, with orthogonal linear polarizations. The polarization of the resulting total field is spatially modulated with a period $\lambda/2$. Every $\lambda/4$, it changes from σ^+ to σ^-. In between, it is elliptical or linear. b–Light shifts and optical pumping transfers (vertical arrows) for an atom having two Zeeman sublevels $M_g = \pm 1/2$ in the ground state and put in such a laser configuration. The spatial modulation of the laser polarization results in correlated spatial modulations of the light shifts of the two sublevels and of the optical pumping rates between them. Because of these correlations, a moving atom can run up potential hills more frequently than down (double arrows).

remain at its maximum value during the whole deceleration process. Continuous beams of slow atoms can be easily obtained in this way. Atomic beams can even be completely stopped over distances of the order of one meter.

3.2 Spatially modulated Zeeman splittings. Sisyphus cooling and optical lattices.

We describe now a laser cooling mechanism using spatially modulated Zeeman splittings due to light shifts produced by a laser light whose polarization is spatially modulated. Consider for example the laser configuration of

Fig. 6.a, consisting of two counterpropagating plane waves along the z-axis, with orthogonal linear polarizations and with the same frequency and the same intensity. At a certain position z_0 along the z-axis, the phase difference between the electric fields of the two waves is equal to $\pi/2$, so that the total field is σ^+–polarized. A distance $\lambda/4$ farther, at $z = z_0 + \lambda/4$, the phase difference between the two fields has increased by π and becomes equal to $3\pi/2$, so that the total field is σ^-–polarized, and so on. Every $\lambda/4$, the light polarization changes from σ^+ to σ^- and vice versa. In between, it is elliptical or linear.

Consider now the simple case where the atomic ground state has an angular momentum $J_g = 1/2$. As shown in subsection (2.4), the two Zeeman sublevels $M_g = \pm 1/2$ undergo different light shifts, depending on the laser polarization, so that the Zeeman degeneracy in zero magnetic field is removed. One can always choose the detuning δ between the laser frequency and the atomic frequency so that, in the places where the polarization is σ^+ (resp. σ^-), the sublevel $M_g = -1/2$ (resp. $M_g = +1/2$) is above the sublevel $M_g = +1/2$ (resp. $M_g = -1/2$). We get in this way the energy diagram of Fig. 6.b showing spatial modulations of the Zeeman splitting between the two sublevels with a period $\lambda/2$.

If the detuning δ is not too large, there are also real absorptions of photons by the atom followed by spontaneous emission, which give rise to optical pumping transfers between the two sublevels, whose direction depends on the polarization: $M_g = -1/2 \longrightarrow M_g = +1/2$ for a σ^+ polarization, $M_g = +1/2 \longrightarrow M_g = -1/2$ for a σ^- polarization. Here also, the spatial modulation of the laser polarization results in a spatial modulation of the optical pumping rates with a period $\lambda/2$ (vertical arrows of Fig. 6.b).

The two spatial modulations of light shifts and optical pumping rates are of course correlated because they are due to the same cause, the spatial modulation of the light polarization. These correlations clearly appear in Fig. 6.b. With the sign chosen for the detuning, optical pumping always transfers atoms from the higher Zeeman sublevel to the lower one. This can lead to a very efficient cooling mechanism, called "Sisyphus cooling" or "polarization gradient cooling"[26, 27] (see also [25]). Consider an atom moving to the right and starting from the bottom of a valley, for example in the state $M_g = +1/2$ at a place where the polarization is σ^+. The atom can climb up the potential hill and reach the top of the hill where it has the maximum probability to be optically pumped in the other sublevel, i.e. in

the bottom of a valley, and so on (double arrows of Fig. 6.b). Like Sisyphus in the Greek mythology, the atom is running up potential hills more frequently than down. When it climbs a potential hill, its kinetic energy is transformed into potential one which is then dissipated by light, since the spontaneously emitted photon has an energy higher than the absorbed laser photon (anti–Stokes Raman processes of Fig. 6.b). Such a cooling mechanism is very efficient and can lead to temperatures T on the order of a few microkelvins, given by $k_B T \simeq U_0$, where U_0 is the depth of the optical potential wells of Fig. 6.b, i.e. the maximum differential light shift. Equation $k_B T \simeq U_0$ cannot remain valid when U_0 tends to zero, because we have neglected the recoil due to the spontaneously emitted photons. There is a threshold for U_0, on the order of a few recoil energies $E_R = \hbar^2 k^2 / 2M$, below which Sisyphus cooling can no longer work.

Note finally that, for the optimal conditions of Sisyphus cooling, atoms become so cold that they get trapped in the quantum vibrational levels of the potential wells of Fig. 6.b. More precisely, one must consider energy bands in this periodic structure [28]. Experimental observation of such a quantization of atomic motion in an optical potential has been first achieved at one dimension [29, 30]. Atoms then form a spatial periodic array, called "1D–optical lattice", with an antiferromagnetic order, since two adjacent potential wells correspond to opposite spin polarizations. 2D and 3D optical lattices have been achieved subsequently (see the review papers [31, 32]; see also the contribution of A.Hemmerich in this volume).

3.3 The magneto-optical trap (MOT)

We describe now an example of a trap for neutral atoms which uses the radiation pressure force $\mathbf{F}$ already mentioned in subsection (3.1) and resulting from the exchanges of linear momentum between atoms and photons in resonant absorption-spontaneous emission cycles. Other types of radiative forces can be used for trapping atoms, the so-called dipole or gradient forces which result from position dependent light shifts or dressed-state energies [25, 33]. But they require in general higher intensities. Using radiation pressure, which is a resonant process, one can hope to build deeper and larger traps.

In most cases, the radiation pressure force $\mathbf{F}$ is simply proportional to the Poynting vector $\mathbf{G}$ of the laser field. This is the case when the induced dipole

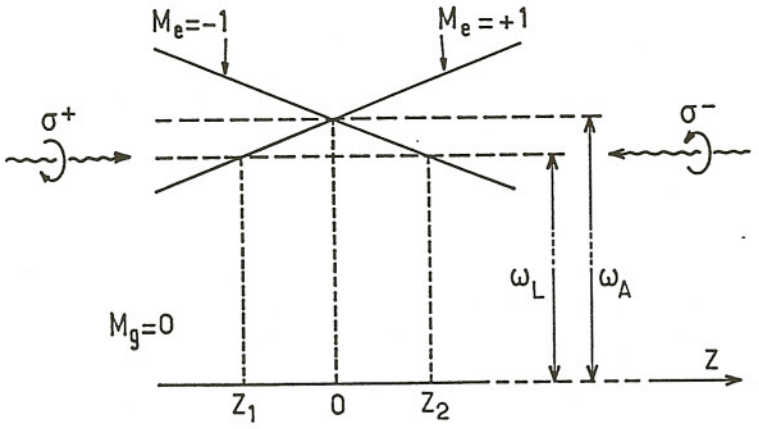

Figure 7: Principle of a one-dimensional magneto-optical trap. An atom with a transition $J_g = 0 \longrightarrow J_e = 1$ is put in a magnetic field gradient along the z-axis and is irradiated with two couterpropagating waves, with a red detuning ($\omega_L < \omega_A$) and with opposite circular polarizations σ^+ and σ^-. The two waves are resonant in different places $z = z_1$ and $z = z_2$, so that the two radiation pressure forces are not balanced, giving rise to a restoring force.

moment $\mathbf{d}$ is proportional to the laser electric field $\mathbf{E}_L$. Condition $\nabla.\mathbf{G} = 0$ then results in $\nabla.\mathbf{F} = 0$: the radiation pressure force is divergence-free. This means that $\mathbf{F}$ cannot be a restoring force in all directions and that stable traps cannot be achieved with radiation pressure forces. Such a result is known as the optical Earnshaw theorem [34].

In fact, it is possible to overcome such a limitation. Suggestions have been made to change the proportionality between $\mathbf{d}$ and $\mathbf{E_L}$ in a position-dependent way using external fields or optical pumping, so that $\nabla.\mathbf{F}$ no longer vanishes [35].

It is here that position dependent Zeeman shifts can be very useful, as suggested first by Jean Dalibard in 1986 with the following one-dimensional scheme (see Fig. 7). Consider an atom with a transition $J_g = 0 \longrightarrow J_e = 1$, put in a magnetic field gradient along the z-axis and irradiated with two couterpropagating waves, with a red detuning ($\omega_L < \omega_A$) and with opposite circular polarizations σ^+ and σ^-. Because of the polarization selection rules, the σ^+ wave excites only the transition $M_g = 0 \longrightarrow M_e = +1$, whereas the

σ^- wave excites only the transition $M_g = 0 \longrightarrow M_e = -1$. The spatial variation of the energy of the sublevels $M_g = \pm 1$ and the non zero value of the detuning ($\omega_L \neq \omega_A$) result in the fact that the two waves cannot be resonant at the same place : the σ^+ wave is resonant with the transition $M_g = 0 \longrightarrow M_e = +1$ at $z = z_1$, whereas the σ^- wave is resonant with the transition $M_g = 0 \longrightarrow M_e = -1$ at $z = z_2$ (see Fig. 7). It follows that the radiation pressure forces of the two waves are not balanced. The radiation pressure force of the σ^+ wave predominates at $z = z_1$, whereas the radiation pressure force of the σ^- wave predominates at $z = z_2$. This results in a restoring force towards the point $z = 0$ where the two sublevels $M_e = \pm 1$ cross. Atomic motion is thus confined in a zone $z_1 \leq z \leq z_2$ whose width $z_2 - z_1$ can be adjusted by varying the detuning $\delta = \omega_L - \omega_A$. Furthermore, the non zero value of the detuning provides a Doppler cooling [36, 37].

In fact, such a scheme can be extended to three dimensions and leads to robust, large and deep traps [38]. It combines trapping and cooling, it has a large velocity capture range and it can be used for trapping atoms in a cell [39]. With all these advantages, the MOT has become the "workhorse" trap in laser cooling.

3.4 Magnetostatic traps

Magnetostatic traps use purely magnetic forces for trapping neutral atoms. These magnetic forces are those which are responsible for the Stern-Gerlach effect. They are due to spatially dependent shifts $E_M(\mathbf{r})$ of the ground state Zeeman sublevels, giving rise to M-dependent forces $\mathbf{F}_M(\mathbf{r}) = -\nabla E_M(\mathbf{r})$. Using these forces for controlling the motion of neutral particles has been suggested and used by several authors [40, 41, 42, 43].

To make a trap with purely magnetic forces, one must achieve a magnetic field configuration exhibiting a local extremum of the modulus $\mid \mathbf{B} \mid$ of the magnetic field $\mathbf{B}$. In fact, it can be shown that a local maximum of $\mid \mathbf{B} \mid$ in a source-free region cannot exist [44]. Only local minima can be achieved, giving rise to trapping of "low field seekers" atoms.

The depth of magnetostatic traps is rather small. For a magnetic moment of one Bohr magneton μ_B, and for a field depth B of 200 Gauss, equation $\mu_B B = k_B T$ gives T=13 mK. This is why magnetostatic traps can work only with precooled atoms. The first magnetostatic trap for atoms to be demonstrated was for laser precooled sodium atoms [45]. Magnetostatic trapping

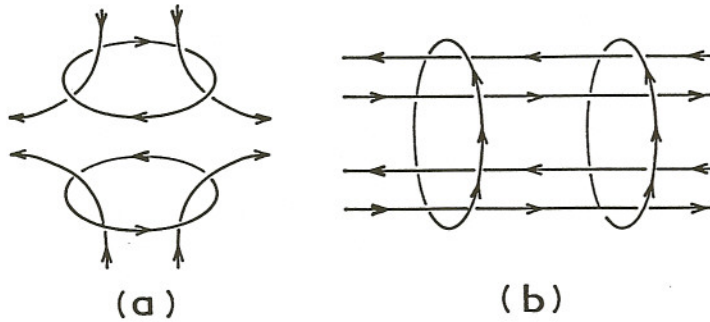

Figure 8: Examples of magnetostatic traps : the quadrupole trap (Fig.a) and the Ioffé-Pritchard trap (Fig.b).

has been also achieved for polarized hydrogen atoms precooled by cryogenic techniques [46, 47] (for a review of atom traps, see [48]).

Fig. 8 gives two examples of magnetostatic traps. The quadrupole trap (Fig.8a) consists of two identical coils with the same axis and with opposite currents. The magnetic field $\mathbf{B}$ vanishes at the center of symmetry $\mathbf{r} = \mathbf{0}$ and its modulus increases linearly with the distance from this point along the three principal axes. Near $\mathbf{r} = \mathbf{0}$, the moving spin cannot follow adiabatically the spatial changes of $\mathbf{B}$ and there are leaks due to Majorana transitions to non trapping spin states. Two methods have been used for overcoming this difficulty. In the first one, a rotating RF field is added so that the "hole" of the trap is rotating sufficiently rapidly for preventing atoms from moving into it [49]. In the second method, the hole of the trap is plugged by a detuned focussed laser beam introducing a repulsive potential [50]. The Ioffé-Pritchard trap (Fig.8b) consists of a four parallel wire configuration producing a confining transverse quadrupole field in the plane perpendicular to the wires, and of two identical coils with the same axis parallel to the wires and with identical currents. These two coils provide a confining longitudinal field, parallel to the wires, near the center of the trap $\mathbf{r} = \mathbf{0}$ [43]. The modulus of the field no longer vanishes. It increases quadratically with the distance from the center of symmetry along the three principal axes and the losses are reduced.

Spectacular developments have occurred recently when magnetostatic trapping of laser precooled alkali atoms was combined with evaporative cool-

ing, leading to the observation of Bose-Einstein condensation [51, 50] and quantum degeneracy effects [52]. We refer the reader to the contributions of C.Wieman and W.Ketterle in this volume for a review of the most recent developments in this field. With the MOT used for capturing first the alkali atoms and for precooling them, with the magnetostatic trap then replacing the MOT, the Zeeman effect plays an essential role in these achievements. One can hope that magnetic couplings will continue to find new applications in this domain. For example, it has been suggested that the scattering length for alkali atoms in the lower hyperfine state could be tuned by an external magnetic field around a Feshbach resonance [53, 54]. In view of the importance for BEC of the scattering length, and in particular of its sign, such a possibility would be very attractive.

4 Conclusion

From the various examples discussed in this paper, one can try to point out a few general trends in the evolution of the modern researches using the Zeeman effect.

Rather than being considered only as a source of informations on the structure of atoms, the Zeeman effect has now become a very useful tool for manipulating them. Extensive studies have been first devoted to the control of the internal degrees of freedom : spin polarization and energy of the Zeeman sublevels. More and more attention is paid now to the evolution of the translational degrees of freedom. In fact, there is a certain continuity between these two types of studies, since many effects dealing with internal variables, such as optical pumping and light shifts, turn out to play an important role in new cooling and trapping schemes, such as Sisyphus cooling. With the recent observation of BEC and the production of condensates of atoms, a new research field is being opened, where magnetic couplings will certainly play an important role.

We finally mention a few important spectroscopic applications of the Zeeman effect which are discussed in other contributions in this volume : the investigation of the energy diagram of Rydberg states in high magnetic fields, when the magnetic energy becomes on the order of the Coulomb energy or larger (contribution of J.Delos); the magnetic resonance imaging using optically pumped nuclei in magnetic field gradients (contribution of E.Otten).

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